Preliminary Research from a Spatial and Dynamic Hydrology/Economic Model for Dryland Salinity

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Abstract: The majority of past hydrological models of dryland salinity for economic modelling have been based on broad and simple assumptions of the hydrological systems of an area. This paper presents the hydrology component of a spatial and dynamic model which aims to compare economic instruments for land use change to abate the off-site impacts of salinity on public assets. Preliminary research is presented on this hydrology component from the use of the method, metamodelling.

Keywords: *dryland salinity; economic modeling; metamodelling; policy*

1. INTRODUCTION

Numerous models have been applied to investigate various aspects of dryland salinity in hydrology, plant sciences, soil sciences and the social sciences. There appears to be no consensus as to which models give the best representation of this phenomenon. Due to the uncertainty over the appropriate models to apply, economists have attempted to model the hydrological impacts of dryland salinity, in an effort to understand the impact on agents affected. These models in most cases assume a simple 'bucket' process, where water enters the ground up hill and exits down hill, causing dryland salinity. This approach is obviously a simplication, ignoring lateral flow, soil types or geological features of the landscape. These simplified models have been developed as hydrology models were judged to be too large and complex to allow economic analyses.

One method for making these large, complex hydrological simulation models manageable is metamodelling. It has been used to reduce the complexity and execution time of process based biophysical models to allow the combination of biophysical and economic models for analyses (e.g. Bouzaher et al., 1993). The purpose of this research is to develop a conceptual spatial and dynamic metamodel of a catchment in the Western Australian Wheatbelt affected by dryland salinity, with the eventual goal of identifying economic instruments that are efficient at altering landholders' land use to reduce dryland salinity in the area. This paper only focuses on the hydrological component of the metamodelling conducted.

First a brief review will be given of past studies at modeling the hydrological component of dryland salinity for economic analyses. Following this, metamodelling will be explained as an alternative method of including the hydrology component into economic analysis. Current research will be presented from the metamodelling of a hydrology simulation model for the WA Wheatbelt.

1.1 Previous Hydrology Models for Dryland Salinity

The majority of past hydrological models of dryland salinity for economic modeling have been based on broad and simple assumptions of the hydrological systems of an area (e.g. Salerian, 1991; Greiner et al., 2001). However, a few studies (e.g. Gomboso et al., 1992; Bell et al., 2001) have employed sophisticated hydrology models to predict the occurrence of dryland salinity. In many instances the economic analysis is not a major component of the study (due to the complexity of the hydrology component) and tends to be a benefit-cost analysis or net present value study.

Subsequently, there is a trade-off between the complexity and effectiveness of the hydrology model and the economic model. As such there is a need to develop a method to reduce the complexity of hydrology models to allow a comprehensive economic analysis of dryland salinity case studies. One such method is metamodelling, which is described in the following section.

1.2 Metamodelling

Metamodels are models of models. Process-based simulation models that are used for hydrology analysis are large complex, nonlinear models with temporal and spatial relationships. Metamodelling involves designing a series of model runs (treatments) to develop an input-output relationship from the process model. This relationship is then applied to regression analysis to develop a simplified regression model (the metamodel) (Kleijnen, 1992; Kleijnen et al, 2000). The resulting metamodel can then be used in a mathematical programming model designed to determine the relative efficiencies of economic policies (Bouzaher et al., 1993). The advantages of this method include reduced data requirements, a simpler functional form, less demanding modeling effort and a high integrative potential (Kleijnen, 1992; Haberlandt et al., 2002). However, the disadvantage is a loss of some accuracy and detail. Depending on the problem at hand, this may or may not be a major concern. Generally the need for accuracy in a metamodel is not as great as for a simulation model (Blanning, 1975).

1.3 Meta-Modeling for Agricultural Pollution Problems

The application of metamodelling to various agricultural and non-point source pollution problems is relatively recent. However it has been used extensively in social science, engineering and medical disciplines. In most cases, metamodelling has been used to decrease the complexity and time consuming nature of a process-based model to investigate different policy situations. For example, Bouzaher et al. (1993) used metamodelling to evaluate agricultural non-point pollution policies. A simple nonlinear exponential function was adequate to explain and predict the simulation model responses for the concentrations of chemicals in groundwater and surface water in the US. In turn, the validated metamodel was incorporated into an agricultural economic decision-making model that allowed various weed management control strategies. Bouzaher et al (1993) judged that in this case, if metamodelling was not used, the policy analysis would have been less comprehensive and thus less adequate to deal with the difficult task of policy formulation.

Similarly, Carriquiry et al. (1998) used metamodelling to reduce the complexity of a sheet and rill erosion process model. Their metamodel did have evidence of lack of fit, however the results estimated and predicted by the model were equivalent to the process model. Additionally, Haberlandt et al. (2002) and Kampas et al (2002) used metamodelling to assess nitrate emissions, in two different situations, to assess different management strategies. Their results confirmed a strong correlation between the process-based model and the metamodel, reinforcing the appropriateness of methodology to conduct policy analyses.

1.4 Significance for Dryland Salinity

Obviously, metamodelling has been used successfully to represent complex process models of environmental systems, as described above. This suggests that metamodelling may be useful in decreasing the complexity of hydrology models for salinity. The following section describes the WA Wheatbelt and the occurrence of dryland salinity as an externality, and also why the Date Creek subcatchment was chosen as a representative area of the Wheatbelt.

2. WA WHEATBELT AND THE PRESENCE OF EXTERNALITIES

Salinisation of the WA Wheatbelt is controlled by hydrogeological processes that affect the distribution of recharge and control the transmission of water and pressure within the saturated zone of the soil (Coram, 1998). An analysis conducted by George et al. (2001) in the wheatbelt region of WA found that catchments in the western region would respond to recharge reduction from different land management strategies more quickly and to a greater extent than the eastern and central wheatbelts. The hydrology model used was Flowtube, a model that has been extensively used in the WA Wheatbelt.

Dryland salinity can be classified as a spatially distributed pollutant (point and non-point) that has externality effects on many public and private assets in the agricultural landscape. However externalities may not be as prominent as previously believed in the WA wheatbelt due to low amounts of groundwater moves across farm boundaries and low slopes and low transmissivity of soils means that treatments are sometimes effective only locally (Pannell et al., 2001).

The research by George et al (2001) supports the ideas expressed by Pannell et al (2001), in that the presence of externalities may not be as evident in the Eastern and Central Wheatbelt, but more obvious in the Western Wheatbelt. This suggests that the application of economic instruments may be more relevant to this area of the Wheatbelt, and other approaches are appropriate to other sections of the Wheatbelt. Therefore, the Date Creek Subcatchment was chosen as a representative catchment for a generic model of the Western Wheatbelt. The following section explains the hydrology model, Flowtube, provides a summary of Date Creek and the metamodelling that was conducted.

3. REGRESSION OF A HYDROLOGY SIMULATION MODEL

3.1 Flowtube Simulation Model

Flowtube was chosen as the representative hydrology model (after extensive investigation into other potential 2D and 3D models) as it has been successfully applied to the WA Wheatbelt (George et al., 2001a; George et al., 2001b) and easily manipulated by the authors. Argent (2001) provides a more in-depth description of the Flowtube hydrology model for the WA Wheatbelt.

The model assumes that the groundwater body can be separated into a number of flow tubes, each of which represents the thickness of the soil above the bedrock and describes a single flow line in a flow net (Figure 1). For each site modeled the flow tube is divided into a number of cells of equal length (this length depends upon the overall length of the flow tube). Groundwater movement between cells is controlled by the Boussinesq diffusion equation:

$$\frac{\partial}{\partial x}\left(K_x\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_x\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_z\frac{\partial h}{\partial z}\right)=S_s\frac{\partial h}{\partial t}-R \qquad (1)$$

where this partial differential equation aims to construct a 3D distribution of heads (h) (the pressure exerted by a liquid), hydraulic conductivities (K) and storage properties (S and R) everywhere within the groundwater system (Anderson et al., 1992).

Initial and boundary conditions are imposed for the differential equation for the starting water level and conditions for each end of the flow tube. Areas at risk of salinising are calculated to occur where the watertable comes within one meter of the soil surface. Each simulation is for a period of 100 years and the watertables converge as equilibrium is reached (George et al., 2001).

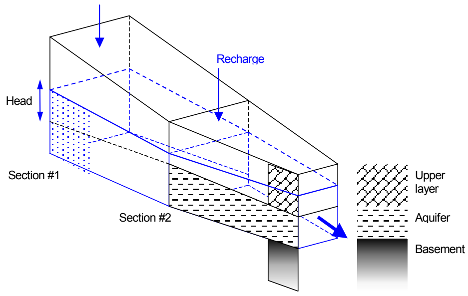

Figure 1: Representative diagram of the Flowtube model. Source: (Argent, 2001)

For each cell along the flow tube, the annual land use provides the default recharge value. To implement an alternative land use, the recharge value is specified as a proportion of the original annual recharge value.

3.2 Date Creek Subcatchment

The Date Creek Subcatchment is one of the most researched catchments in Western Australia. It is a subcatchment of the Blackwood River Catchment, located within the West Arthur Management Zone. Grazing annual pastures for wool, lamb and beef production are the predominant industries. Only limited areas of perennial species presently exist at any site, with Date Creek having 20% of its catchment covered by woody vegetation (George et al., 2001). Commercial tree crops (E.globulus and Pinus pinaster) are currently grown near Date Creek. Its annual rainfall is 600mm/yr and potential evaporation of 1500mm/yr.

4. METHODS

4.1 Flowtube Simulation

The Flowtube model was run several times for differing combinations of proportion of perennial cover (0, 5, 10, 15, 20, 40, 60, 80 and 100) and recharge proportions (0.05, 0.1, 0.3, 0.5 and 1). Each simulation was run for 100 years, in 5 year time steps. Results were gathered (in Excel) showing the head of the watertable every 50m along the Date Creek cross section (3300m), for each time step starting at time zero. Figure 2 shows that the simulated results follow a non linear functional form.

4.2 Estimation Approach

For the analysis, the model developed was an estimation of (1), where the following variables were approximated, where K and R were approximated by the proportion of area covered (C) and proportion of recharge (R) to develop CR;

x,y and z was approximated by the distance from start of the cross section (D) and time (T); S and h were approximate by the depth to watertable (W) in meters and head (H) in meters, depending upon the simulation run.

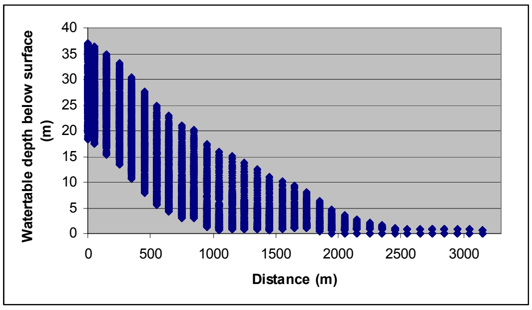

Figure 2: Flowtube simulation data showing a non linear functional form for watertable depth over the distance of the cross section.

Estimate of the output from the simulation model involved two approaches. The first, *two equations approach*, was aimed at fitting a model to the change in H_t at D=0, that is the top of the catchment, using a lagged endogenous variable, H_{t-1}, function:

$$H_t = \beta_1 H_{t-1} + \beta_2 CR + \beta_3 CR^2 + \varepsilon \quad (2)$$

Secondly, analyses were conducted to determine if W_t at D=0 would be able to predict W_t at other distances down the cross section. A quadratic functional form was considered to be the most appropriate, as the observed data is obviously non linear (Figure 2). The quadratic equations fitted were:

$$H_{td} = \beta_1 + \beta_2 H_{t0} + \beta_3 H_{t0}^2 + \beta_4 CR + \beta_5 CR^2 + \beta_6 D + \varepsilon \quad (3)$$

$$H_{td} = \beta_1 + \beta_2 H_{t0}^2 + \beta_3 CR + \beta_4 CR^2 + \beta_5 D^2 + \varepsilon \quad (4)$$

$$H_{td} = \beta_1 + \beta_2 H_{t0} + \beta_3 CR^2 + \beta_4 D + \varepsilon \quad (5)$$

The second, *single equation approach,* was to treat the data set as a whole, not as one section determining W_t along the cross section. Time was also included into many of these equations, as the watertable depth occurs specifically at specific T and D. The watertable depth was determined by the following functional forms:

$$W_{td} = \beta_1 + \beta_2 D + \beta_3 CR + \beta_4 T + \varepsilon \quad (6)$$

$$W_{td} = \beta_1 + \beta_2 D + \beta_3 D^2 + \beta_4 CR + \beta_5 CR^2 + \beta_6 T + \beta_7 T^2 + \varepsilon \quad (7)$$

$$W_{td} = \beta_1 + \beta_2 D + \beta_3 D^2 + \beta_4 D^3 + \beta_5 CR + \beta_6 CR^2 + \beta_7 T + \beta_8 T^2 + \varepsilon \quad (8)$$

$$W_{td} = \beta_1 + \beta_2 W_{t-1,d} + \beta_3 D + \beta_4 D^2 + \beta_5 D^3 + \beta_6 CR + \beta_7 CR^2 + \beta_8 T + \beta_9 T^2 + \beta_{10} T^3 + \varepsilon \quad (9)$$

$$W_{td} = \beta_1 + \beta_2 W_{t-1,d} + \beta_3 D + \beta_4 D^2 + \beta_5 D^3 + \beta_6 CR + \beta_7 CR^2 + \varepsilon \quad (10)$$

In (8), only D was cubed as it had the primary influence on the watertable depth.

5. RESULTS AND COMMENTS

5.1 Two Equation Method

Table 1 presents the results from the first analysis for (2), (3), (4) and (5). Even though all equations were good fits, according to the adj R^2, the residual vs. fitted values plots (for example Equation (4) (Figure 3)), showed that some values were extremely over or underestimated, such that the residuals did not appear as 'white noise', suggesting heteroscedasticity. That is, this approach could not accurately predict the depth of the watertable in the Date Creek Subcatchment over time and spatially. Hence this approach was rejected and the second approach, where the data was treated as a complete set, was investigated.

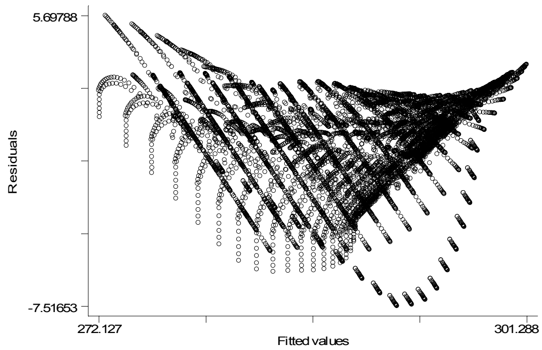

Figure 3: Residual vs fitted value plot for Equation (4) in two equation approach.

5.2 Single Equation Method

Table 2 displays the results from the functional forms (6 to 10) applied to the entire data set obtained from Flowtube. Obviously (6) was not a good fit, as the observed data does not show a linear trend (Figure 2). Equations (7) and (8) are good fits according to the adj R^2, but their residual vs. fitted value plots (for example figure 4 for equation (7)) showed that the values were extremely over or underestimated, such that the residuals did not appear as 'white noise', again suggesting heteroscedasticity. This again implies that the watertable depth over time and space is not accurately represented by these functional forms. However, (9) and (10) displayed good fits statistically and graphically of the residual vs. fitted values plots (for example figure 5 for equation (10)). It is obvious that using a distributed lagged variable (W_{t-1}) is the preferred functional form for determining watertable height over time and spatially.

Table 1: Results from (2-5) showing parameter values *(t-value),* adj R^2 and RMS error.

	EQUATION			
PARAMETERS	(2)	(3)	(4)	(5)
Constant	-	-1484.7 *(-18.5)*	237.6 *(257.5)*	187.3 *(131.5)*
H_{t-1}	1.0 *(422.4)*	-	-	-
H_{to}	-	11.7 *(21.5)*	-	0.4 *(79.3)*
H_{t0}^2	-	-0.2e-1 *(-20.8)*	0.1e-2 *(61.2)*	-
CR	0.3e-1 *(2.7)*	-0.5e-1 *(-6.8)*	-0.2-e-1 *(-2.6)*	-
CR^2	-0.1e-2 *(-2.5)*	0.1e-2 *(4.4)*	0.1e-2 *(2.2)*	-0.1e-3 *(-1.4)*
D	-	-0.1e-1 *(-506.5)*	-	-0.1e-1 *(-498.7)*
D^2	-	-	-0.4e-4 *(-400.5)*	-
Adjusted R^2	0.99	0.95	0.92	0.95
RMS Error	1.1	2.6	3.2	2.6

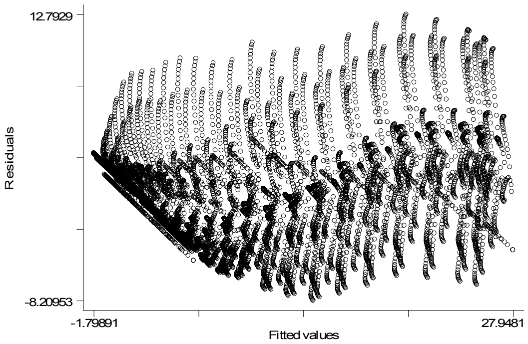

Figure 4: Residuals vs. fitted values plot for (7).

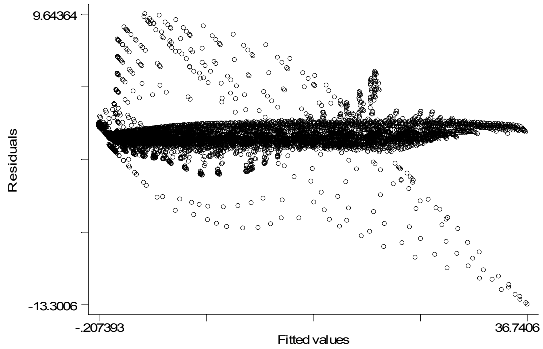

Figure 5: Residuals vs. fitted values plot for (10).

Table 2 Results from (6-10) showing parameter values *(t-valu*e), adj R^2 and RMS error.

	EQUATION				
PARAMETERS	(6)	(7)	(8)	(9)	(10)
Constant	18.1 *(154.8)*	26.0 *(257.7)*	28.6 *(281.8)*	1.8 *(18.0)*	2.0 *(21.9)*
W_{t-1}	-	-	-	0.9 *(302.1)*	0.9 *(300.6)*
T	-0.03 *(-4.1)*	-0.1 *(-6.7)*	-0.1 *(-7.4)*	0.1 *(3.9)*	-
T^2	-	0.44e-2 *(5.0)*	0.4e-2 *(5.6)*	-0.1e-1 *(-4.2)*	-
T^3	-	-	-	2.7e-04 *(5.4)*	-
CR	0.4e-1 *(7.9)*	0.1 *(22.1)*	0.2 *(24.6)*	0.2e-1 *(7.6)*	0.1e-1 *(4.9)*
CR^2	-	-0.4e-2 *(-18.7)*	-0.4e-2 *(-20.8)*	-3.3e-4 *(4.4)*	-3.3e-4 *(-4.5)*
D	-0.7e-1 *(-159.0)*	-0.2 *(-230.7)*	-0.4e-1 *(-160.5)*	0.3e-2 *(-18.3)*	-2.6e-3 *(-18.7)*
D^2	-	5.4e-6 *(165.5)*	1.5e-5 *(88.9)*	1.1e-6 *(13.6)*	1.1e-6 *(13.9)*
D^3	-	-	-2.1e-9 *(-58.1)*	-1.5e-10 *(-9.9)*	-1.5e-10 *(-10.2)*
Adjusted R^2	0.64	0.88	0.90	0.99	0.99
RMS Error	5.3	3.1	2.8	1.0	1.0

Obviously (10) is not concluded and still needs further analysis, however Figure 6 is encouraging as there are fewer outliers and the evidence of heteroscedasticity is minimal. Further estimation methods were applied to the data, including Tobit, however additional analysis is required.

7. CONCLUSIONS

The results presented in this paper are encouraging. They suggest that metamodelling may be a valuable technique to decrease the complexity and time consuming nature of current hydrology model for dryland salinity and to improve its ease of application to economic analyses. It is hoped that the construction of a hydrology metamodel with its incorporation into an economic model will provide a comprehensive assessment of various economic instruments for dryland salinity reduction or prevention.

8. ACKNOWLEDGEMENTS

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9. REFERENCES

Anderson, M. P. and Woessner, W. W. (1992). *Applied Groundwater Modelling: Simulation of Flow and Advective Transport*. California, Academic Press Inc.

Argent, R. (2001). *Flowtube Groundwater Calculator: User Manual*. Perth, Agriculture Western Australia.

Bell, R. and Heaney, A. (2001). "A basin scale model for assessing salinity management models." ABARE working paper 2001.A.

Blanning, R. W. (1975). "The construction and implementation of metamodels." *Simulation* 24: 177-184.

Bouzaher, A., Lakshminarayan, P., Cabe, R., Carriquiry, A., Gassman, P. and Shogren, J. (1993). "Metamodels and nonpoint pollution policy in Agriculture." *Water Resources Research* 29(6): 1579-1587.

Carriquiry, A., Breidt, F. and Lakshminarayan, P. (1998). "Sampling schemes for policy analyses using computer simulation experiments." *Environmental Management* 22(4): 505-515.

Coram, J. (1998). *National Classification of Catchments for Land and River Salinity Control*. Canberra, RIRDC.

George, R., Clark, C. and Hatton, T. (2001). " Computer modelled groundwater response to recharge management for dryland salinity control in Western Australia." *Advances in Environmental Monitoring and Modelling* 2(1): 3-35.

George, R. and Coleman, M. (2001). Hidden menace or opportunity-Groundwater hydrology, playas and commercial options for salinity in wheatbelt valleys. Wheatbelt Valleys Conference.

Gomboso, J. and Ghassemi, F. (1992). "Groundwater modelling and optimal salinity controlling the north Stirling land conservation district Western Australia." *Mathematics and Computers in Simulation* 33: 609-614.

Greiner, R. and Cacho, O. (2001). "On the efficient use of a catchments land and water resources: dryland salinization in Australia." *Ecological Economics* 38(3): 441-458.

Haberlandt, U., Krysanova, V. and Bardossy, A. (2002). "Assessment of nitrogen leaching from arable land in large river basins. Part 2. regionalisation using fuzzy rule based modelling." *Ecological Modelling* 150: 277-294.

Kampas, A. and White, B. (2002). "Emission versus input taxes for diffuse nitrate pollution control in the presence of transaction costs." *Journal of Environmental Planning and Management* 45(1): 129-139.

Kleijnen, J. (1993). "Sensitivity analysis of simulation experiments: regression analysis and statistical design." *Mathematics and Computers in Simulation* 34: 297-315.

Kleijnen, J. and Sargent, R., (2000). “A methodology for fitting and validating metamodels in simulation.” European Journal of Operational Research 120:14-29.

Pannell, D., MacFarlane, D. and Ferdowsian, R. (2001). "Rethinking the externality issue for dryland salinity in Western Australia." *Australian Journal of Agricultural and Resource Economics* 45(3): 459-475.

Pavelic, P., Dillon, P., Narayan, K., Herrmann, T. and Barnett, S. (1997). "Integrated groundwater flow and agronomic modelling for management of dryland salinity of a coastal plain in southern Australia." *Agricultural Water Management* 35: 75-93.

Salerian, J. S. (1991). *Economic analysis of dryland soil salinity in a subcatchment in Western Australia*. Department of Economics. Crawley, University of Western Australia.